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Synthesis of spray booth control software in programmable controller

***Abstract**. The purpose of this article is to present the achievements in the field of control system design methodology and the development of algorithms for control functions of the a spray booth based on an operator panel integrated with a PLC controller, i.e. in conditions of limited data and program memory and limited programming language syntax.*

***Streszczenie.** Celem niniejszego artykułu jest przedstawienie dokonań w zakresie metodyki projektowania systemu sterowania oraz opracowania algorytmów dla potrzeb sterowania funkcjami kabiny lakierniczej na bazie panelu operatorskiego zintegrowanego ze sterownikiem PLC tj. w warunkach ograniczonej pamięci programu i danych oraz ograniczonej syntaktyki języka programowania. (**Synteza oprogramowania sterującego kabiny lakierniczej w sterowniku programowalnym**).*

Keywords: programmable controller, control software, hardware synthesis, software synthesis.
Słowa kluczowe: sterownik programowalny, oprogramowanie sterujące, synteza sprzętowa, synteza programowa.

Introduction

Development of the control software, including the implementation of control algorithms for plants, operating in real time, is preceded by a hardware synthesis, i.e. the choice of automation components (sensors, actuators and control devices) based on the end user functional requirements. Usually hardware architecture has influence on the choice of the control software structure.

In the initial phase of development all control programs, implemented in memory PLCs have a linear structure, but with the evolution of programming languages has become possible structural programs writing.

Structural design methods provide suggestions to the decomposition of programs into smaller and easier to implement modules. In this method, programs can be created on the basis of well-defined functional requirements, precisely defining acceptable solutions of the problem. Implementation of the such written program is related to call subroutines from the main part of the program.

This article will present the achievements in the field of synthesis of hardware and software connected with a spray booth control system. It should be noted that during the start-up of the control system such problems like: measurement noise, random noise, delays of actuators, etc. arise, which require modification originally assumed control system functions.

A controlled system description

The task of the refinishing spray booth is to ensure a safety and comfort of the painter. During a painting process inside the painting chamber the air is constantly exchanged. Fresh air blown up inside the spray booth is fixed by air make up unit. The fresh air is cleaned and heated. Inside the working area there is a small overpressure, it prevents to get in pollutants through a small leaks or open door. During drying mode air is circulating in the closed loop, and about 10 percent of the air is freely refreshed.

The basic tasks of spray booth' control system is: actuators control, work condition parameters control, supervising on the safety of painter and the process, indicating of emergency.

The control system in the simple version control only a few parameters: blowing fan, extraction fan, control of overpressure and temperature inside working area, positions of the dampers installed inside ventilation ducts. Current state of the art in control systems enables to create much more advanced control systems with moderate expenses. The control system can be extended of additional function blocks for example: the overpressure control [4], more precisely control of temperature, access to pressed air during painting mode, control and indicating of the air filters pollution, control and indicating of safety conditions [7], register and analysis of work condition parameters. On the basis of registered parameters a PLC controller can analyze dynamic changes of individual parameters [2]. Correctly implemented auto tuning functions enable adaptive update of controller's settings for individual processes.

Modern user interfaces mostly base on touch panels. It enables an easy communication between user and a spray booth. Current solutions of control systems take into consideration two basic parameters:

- air temperature,
- overpressure inside working area.

A concept of the modern control system of the spray booth is widely described in [1,2].

For a temperature control there are different control strategies [3,9], but the spray booth' dynamic must be known. A spray booth is a multi inertial plant with variable dynamic. Three basic inertias can be presented:

- a burner inertia,
- heat exchanger inertia,
- spray booth construction inertia.

The transfer function $G_T(s)$ temperature control can be presented by equation:

$$G_T(s) = \frac{K_b K_h K_c}{(1+sT_b)(1+sT_h)(1+sT_c)} \tag{1}$$

where: K_b – burner magnitude, K_h – heat exchanger magnitude, K_c – spray booth construction magnitude, T_b – burner inertia, T_h – heat exchanger inertia, T_c – spray booth construction inertia,

The burner magnitude K_b is constant and depends on power of burner. In real object the burner magnitude can be variable in a small range in case of calorific value and burner' technical condition. The burner inertia T_b depends on oil pump and ignition time, it is small enough to be neglected without any consequence in temperature control quality. The heat exchanger magnitude K_h depends on its efficiency. Inertia of heat exchanger T_h is correlated with volume of fresh air flow and its temperature. Spray booth construction magnitude K_C is smaller than 1 and inertia of construction depends of its material, mass and area.

There are various constructions of burners and heat exchangers or direct burners without heat exchangers [7].

The overpressure linear model can be also represented by transfer function of second order inertial object:

$$G_O(s) = \frac{K_F K_A}{(1+sT_F)(1+sT_A)} \tag{2}$$

where: K_F, T_F – the dynamic parameters of the fan, K_A, T_A – the dynamic parameters of air flow ducting.

The fan performance has main influence for the overpressure control dynamic. The next important parameter for overpressure dynamic is a dynamic of the air flow ducting [6]. The parameters of air flow ducting transfer function are constantly changing in case of filters contamination.

There are high interactions between overpressure and temperature dynamics.

A heat recovery installation also has a high impact on the dynamics of air temperature and overpressure control. In refinishing paint spray booths cross recuperators are the most often used for heat recovery [5]. Heat recovery completely changes the thermal dynamic of spray booth and cause air flow resistance. Air flow resistance changes the overpressure dynamic control.

Additionally the overspray sediments have an influence on dynamic of controlled parameters [5,6]. The overspray sediments created on the fan blades change geometry of blades, it results in change of fan performance. The overspray sediments are also created on recuperator wall, it bring the heat transfer resistance [6,8] and increase the air flow resistance.

The dynamic of temperature and overpressure control is also depending on work mode of the spray booth.

In case of changeable dynamic of the spray booth, the modern control system of refinishing spray booth should have supervisor system, which updates controller's settings due the current dynamic. In order to create such control system, the PLC software must have many functional blocks.

Methodology of hardware and software synthesis

To the final control system, including diagrams of devices and a control program, the developer comes through (Fig.1): analysis of technology related to the controlled device or/and process, the user requirements specification, documentation of the project, documentation of the structure of hardware, software and rules for operating and testing of components.

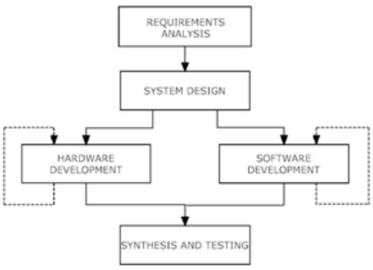

Fig.1. A cyclic development model of the of the control system [13].

Requirements analysis leads to determine system requirements specification, i.e. a document defining functions of the system, accuracy, speed and reliability, restrictions connected with used hardware and software and project costs and expected results of its implementation. It should be emphasized that the analysis requirements cannot impose how to implement the system - has only define its objectives and functions, but in practice, the project budget can greatly affect the accepted concept of the control system. A thorough assessment of the specification reduces the risk of building a system that does not meet the expectations of end users.

At the design stage of the system a developer determines its architecture by dividing the system into components, which are assigned to functions defined in the specification and determines the functions performed by the hardware and software. A modular architecture of the controlled system corresponds well with a structural software design methodology [11], which

- improves the readability of the program;
- will standardize repetitive parts of the program - use of function blocks and data structures;
- provides a simpler implementation, commissioning, testing and modifying the program - each of program block can be created and tested independently;
- allows to create a program in a group of programmers, which shortens the time of creating a new control program or/and modifications.

The development of hardware components can be configured based on standard components and only a small part of the specialized equipment must be designed individually. Otherwise, software components usually have to be designed for each application individually, although may include standard software modules, e.g. stepper motor control module, functions data structures used repeatedly.

Integration and testing includes a making a physical connection of hardware components with a controlled device and / or process and test operation of the system in the target work environment under the control of the control software designed in accordance with the test plan provided for in the system design document. It should be noted that testing usually leads to modification of software components (additional functions, user interface changes, the correction control algorithms, etc.), less hardware (replacement of the measuring equipment and/or actuators, etc.).

Hardware and software synthesis

The task of the developed control system is to control the refinishing spray booth functions, according to the declared requirements. Based on preliminary assumptions, following system functions were identified:

- checking the preconditions necessary for the proper operation of the painting booth,
- communication with the operator - the reception command signalling of various operating states cabins painting and drying modes,
- alarm signalling,
- system of the temperature stabilization inside the cabin,
- system of the pressure stabilization inside the cabin,
- lights control system inside the cabin.

Diagram showing the various machine functions are shown in Figure 2.

According to the diagram (Fig. 2), the operator can interfere in each separate function of the system, although he isn't directly involved in the spray booth process control.

Detailed functions of the control system:

- switching system - preconditions for switching:
  - a properly functioning control system (presence of power, the controller in RUN

mode, the controller program running, set the temperature coating, drying and drying time).

- communication with the operator (operator actions):
  - activation of the system - the power supply, for sensors and actors
  - Control switching on - starts the process, choice of spray booth mode - working in a coating or drying mode
  - alarm reset - the transition from the failover to the state of waiting for the decision of the operator
  - setting coating and drying temperature and drying time.
- signaling process status
  - the system is ready - waiting for switching in the selected mode,
  - system in the coating or drying or emergency state,
  - signaling activity of the selected operating mode,
  - displaying the current temperature and pressure
  - time display until the end of drying and drying
  - alarm - the process stopped - alarm occurs if there are states forbidden e.g. a vacuum inside of the spray booth for a specific period of time.

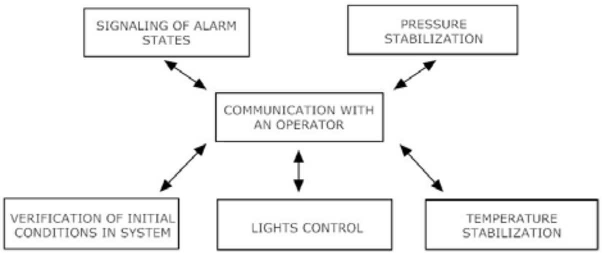

Fig. 2. A functional structure of the control system.

Design of the device starts with the decomposition of the control system to functional modules shown in Figure 3.

The construction of the control system is based on the standard PLC with the panel, which is an executive platform for the control software. After calculating all inputs and outputs for each system component, it turned out that the controller must have at least 6 digital inputs, 4 digital outputs, 2 analog inputs and 2 analog outputs.

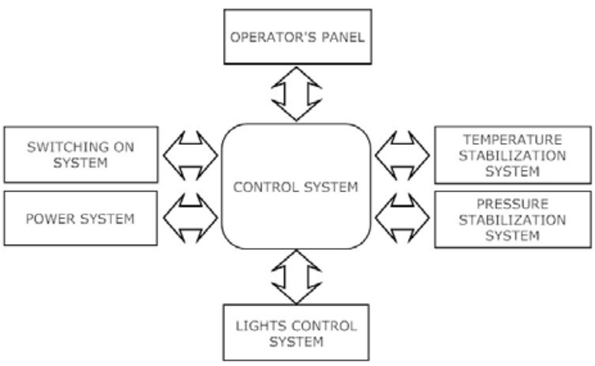

Fig. 3. A functional modules of the spray booth control system.

Switching on system – turns power on for sensors (buttons and switches) and signaling elements (LEDs). The system includes a button and a LED diode:

outputs:	a LED diode "System activated"	1 bit
inputs:	a pushbutton "Activate system"	1 bit

Temperature stabilization system is designed to control the burner to keep the desired temperature related to the specific mode. The system consists of: a burner, a temperature sensor and a throttle drive with sensors, detecting its limit positions.

inputs:	1 temperature measurement	1 word
	throttle position	2 bits
	failure of the burner	1 bit
outputs:	control of the burner	1 bit
	throttle control	1 bit

Pressure stabilization system is designed to control the inlet and outlet fans to keep the desired pressure in any mode. The system consists of: inlet and outlet fans and a pressure sensor.

inputs:	1 pressure measurement	16-bit word
	fans thermostats	2 bits
outputs:	2 fan control	16-bit words

Lights control system is designed for activation of the circuit switching the lights inside the booth.

outputs:	relay closing the lights circuit	1 bit

Operator Panel - containing graphical user interface, allowing selection of the operating mode and configuration of coating and drying parameters and informing about the process state and the mode.

The panel enables following operations:

Switching system – principles of operation, inputs and outputs described in the section switching system;

Entering configuration parameters for control algorithms and for work modes;

Other functions i.e. start and stop operations of a spray booth, the choice of mode - the mode of coating, drying and emergency service alarm conditions, realized using a graphical user interface.

Power system - should provide standard 24VDC power supply to the controller and signaling elements. Power supply must be greater than the sum of the currents of all devices powered from the power supply.

Table 1. A power consumption analysis of elements installed in the control system.

Device	Number of items	Sum of current
Panel controller PLC	1	200 mA
Temperature module	1	50 mA
Relay	6	360mA
Total current		**610 mA**

Based on the analysis, it was found that the maximum current drawn by the control system of the spray booth reaches 610 mA (Table 1). However, due to the fact that no such situation happens that all output devices were switched on at the same time, the actual current drawn from the power supply during operation is much lower. For safety reasons, the power supply used in the control system must have a current capacity equal 2.5A.

Using physical modules program is structurally divided into six functional modules, which are arranged in subroutines called from the main program _MAIN:

- Program organization,
- Switching system,
- Screens,
- Coating,
- Drying,
- Service.

At a time can be executed one subprogram. The fact that the subroutine is implemented, the operator decides – using suitable element of the graphical user interface.

All software modules were created separately and after they tested were combined with the module organizing the program, included in the main program.

Spray booth can be in four modes:

- **the device is not ready** - the system is not switched on - should be supported software module Switching System;
- **the device during programming** - supported service module;
- **the device in the coating mode** - supported coating module;
- **the device in the drying mode** - supported drying module.

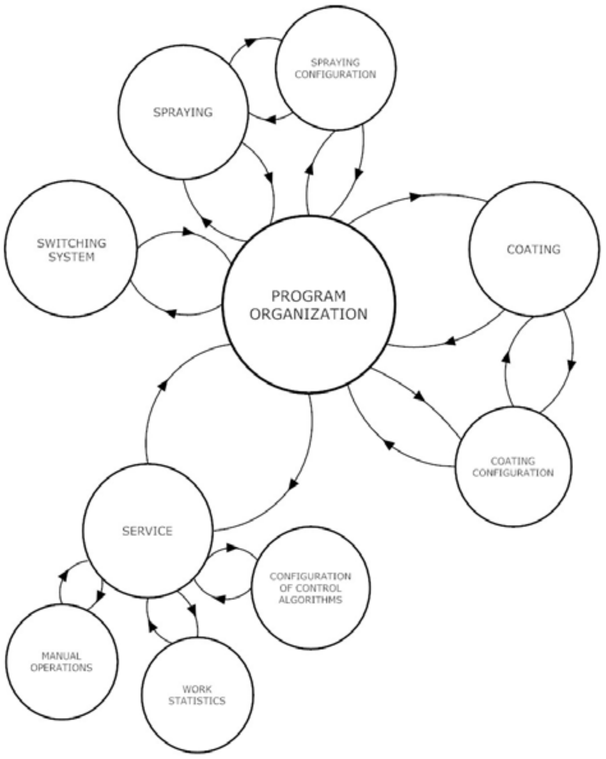

Fig. 4. A structure of the spray booth control system.

For proper organization and correct functioning of the entire program is responsible a software module Program Organization that is included in the main program. Switching coating or drying should be precede by pre-set the system i.e. the temperature of coating, drying and drying time. Moreover, the system must be switching on. During coating and drying modes are executed sub-programs responsible for the temperature and pressure stabilization and the security control.
The programming mode may be switch on when the system is active and coating or drying is in-active and coating or drying is completed. An architecture of the control system is shown in figure 4. Navigation in the system and a graphical user interface is implemented using a subroutine Screens.

In summary it can be seen that the division of the software into modules requires earlier division into hardware modules, according to functional requirements. In this case, it is worth to do a functional analysis of the developed device, selecting a main function and then dividing it into sub-functions.

Conclusions

The main objective of this study was to prove that the division of control software modules, compatible with hardware architecture designed for machine automation, improves the readability of the code, allows multiple use of repeated fragments of the program, makes easier the implementation, commissioning, testing and modification of the program and gives an ability to work in teams, which was presented as an example of the control system described for spray booth.

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